USE OF THE NAVAL HYDROCODE GEMINI TO SIMULATE IN-AIR EXPLOSIONS AND PREDICT SHOCK CONDITIONS IN FIELD FORTIFICATIONS

Jonathan C. Bennett*, William F. Heard, Michael J. Roth, and Ryan D. Stinson
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180

ABSTRACT

This paper presents results from a research and development effort directed toward the enhancement of warfighter capability to perform rapid vulnerability assessments of blast effects (from threats such as car bombs) on field fortifications. This is a capability that does not currently exist in the warfighters' toolkit, and is considered to be of tremendous relevance based on the current operational environment and common mode of enemy attack. The approach to development of this capability is based on use of a first-principles hydrocode as a "virtual test bed" to perform large numbers of shock effects calculations on an expedient protective structure. The hydrocode data is then used to build a statistically generated response surface, which can be implemented in easy-to-use warfighter assessment tools. As an added benefit of this effort, the hydrocode Gemini was used to perform simulations. This code has been primarily developed for use in underwater explosion applications, but is expected to also accurately perform in-air detonation calculations. Therefore, calculational results benchmarked against experimental data provide information that supports expansion of code use to other applications of Army interest.

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1. INTRODUCTION

The current military operating environment, coupled with evolving asymmetric threats, has created an increased focus on warfighter capability to perform rapid, accurate, vulnerability assessments of a near endless array of threat conditions. Accordingly, development of warfighter tools, such as the U.S. Army Engineer Research and Development Center (ERDC) code AntiTerrorism Planner (ATPlanner) (George and Hossley, 2001), to rapidly assess user defined threat conditions has drawn continued focus in the area of force protection research and development.

Codes such as ATPlanner have historically been developed to assess blast effects against conventional fixed construction. Such codes typically yield a damage assessment level based on charge weight and standoff, or conversely define a required standoff to limit damage to specified levels based on user defined structure parameters. Although these predictive capabilities are widely used for conventionally built structures, commensurate capabilities for expeditionary-type structures are yet to be developed. Therefore, to expand the functionality of a code like ATPlanner, the efforts discussed in this paper are directed toward development of an accurate and calculationally inexpensive algorithm to predict blast effects on – and more specifically blast intrusion into – expedient field fortifications.

In general, the approach to development of this algorithm employs the use of a first-principles fluid dynamics code to generate data for the population of a multi-dimensional response surface. The response surface estimates blast effects inside a structure (such as a guard post at a vehicle check point) as a function of user defined parameters such as charge weight, standoff, charge orientation to structure and structure configuration. Using a response surface in this fashion will allow ATPlanner to generate blast effects predictions with potentially greater accuracy than might be obtained with other empirical or ray-tracing schemes, and without the burden of calculational time associated with calculational fluid dynamics (CFD) simulations.

In this effort, the hydrocode Gemini (NSWC, 2005) was selected to perform the CFD calculations. Gemini is supported by the U.S. Naval Surface Warfare Center (NSWC) at Indian Head, MD, and has been primarily developed for, and benchmarked against, underwater explosion simulations. However, it has been expected that the code can also accurately perform in-air simulations, although little information is available to validate the performance. Therefore, successful calculations performed under this effort have as an added advantage the generation of benchmark data for in-air

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detonation Gemini simulations. And if shown to be accurate, this will contribute to the expansion of Army calculational capability through documentation of code performance in simulations of Army interest.

The remainder of this paper presents Gemini modeling results for a high-mass, expedient field fortification exposed to blast effects at a specific scaled range. Numeric pressure predictions inside the structure, and in the free field, are compared to experimentally gathered data for validation of the CFD calculations. The approach to building a predictive response surface with the CFD results is also presented, and experimental data is plotted against the surface to evidence its potential accuracy.

2. FIELD FORTIFICATION

Based on feedback from U.S. forces, high-mass, soil based structures represent one of the most prominent construction types currently in use. For this reason, along with a wealth of data gathered from other experimental activities, the field fortification modeled in this effort was an observation post constructed with soil filled Hesco Bastion® material. From observations of U.S. operations, this structure was considered to be very representative of a field fortification that might be found at a typical U.S. vehicle checkpoint or entry control facility. An example of the observation post is shown in Figure 1.

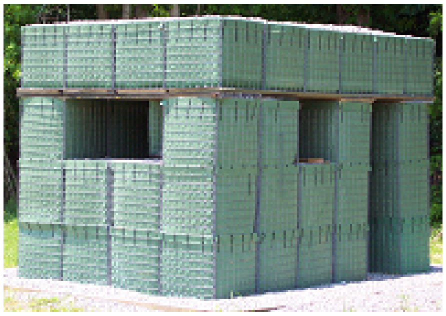

Figure 1. Observation post

Based on the structure's mass, a simplifying assumption was made concerning its vulnerability to blast effects. In general, the hazards posed to occupants in a large blast event result from either 1) structural collapse under dynamic response, or 2) physiological damage incurred by occupants due to shock intrusion into the structure. Considering the structure's mass and nature of construction, it was expected that inertial resistance and ductility in response would allow it to withstand very high shock loadings before experiencing significant structural damage. Furthermore, assuming that the fortification's structural characteristics would allow it to withstand a substantial blast event, it was assumed that the internal shock environment would reach significant physiological hazard levels before reaching a critical structural loading. Based on these assumptions, structural response was not considered during modeling because it was not expected to represent the limit state hazard for position occupants. Modeling was therefore performed solely with Gemini's Eulerian solver, and the structure was represented as a non-responding rigid body in the flow field. Likewise, the response surface was developed from internal shock data, and did not consider structural response as a primary hazard to occupants.

To verify the assumed primary hazard mode, an experiment was conducted in May 2006 as part of an international trial (Trial 859) conducted by the Australian Defence Force (ADF). In this experiment, ERDC constructed a small observation post in close proximity to a large explosive charge. The structure was instrumented with piezoelectric pressure gages to document shock conditions, and post-test observations were used to evaluate structure response. As seen in Figure 2, the structure reached the limit state of structural collapse, but did not experience catastrophic failure. However, internal pressure gages indicated that the shock conditions reached a high probability of lethality based on published physiological response data (Cooper, 1996). From this experiment, it was verified that indeed when attacked with a large explosive charge, the primary threat to occupants of this type structure is shock induced physiological damage, and structural collapse is a secondary hazard.

Even though the structure experienced significant deformation, as seen in Figure 2, the assumption to model it as a non-responding rigid body remained valid for the scenario considered. The reason for this is that even though large structural deformations occurred, due to high structure mass they largely occurred after the internal shock event had taken place. And therefore, the shock conditions governing physiological response would not be affected by the later occurring structural displacements.

Figure 2. Experimental results

3. CFD MODEL

As previously stated, CFD calculations were performed with the hydrocode Gemini. Gemini is the Eulerian component of the DYSMAS suite of codes, which combines Gemini with DYNA-N (2D or 3D) to perform coupled Eulerian/Lagrangian calculations.

For validation purposes, the model was built to simulate a specific physical experiment. In May, 2004, ERDC participated in ADF Trial 845, conducted in Woomera, South Australia. As part of ADF Trial 845, a small observation post was exposed to the effects of a large explosive charge. The charge, shown being built in Figure 3, was constructed in two stacked layers with a relatively large width to depth ratio. The charge was not center-point detonated, as is commonly done, but was simultaneously initiated at multiple surface detonation points uniformly distributed over the charge's surface. Because of this relatively irregular charge shape and non-standard mode of initiation, it was believed that simulation of this particular event provided an excellent opportunity to not only benchmark Gemini's performance under in-air conditions, but also would evidence the code's capability to simulate conditions which cannot be evaluated with simpler empirical tools.

For computational efficiency, Gemini modeling was performed in two separate stages: two-dimensional free field calculations and three-dimensional calculations of the flow field and structure.

To most accurately represent the rectangular charge configuration, a three-dimensional free field domain would need to be used. However, considering the size of the domain, a three-dimensional model of the free field space would incur an enormous calculational cost and was deemed prohibitive (and perhaps unnecessary). Therefore, the free field calculations were performed in a two-dimensional, axisymmetric, cylindrical domain. The domain was discretized with a gradient mesh in both the horizontal and vertical directions. From the origin, cell size was constant over a range of 15 m in both directions. At 15 m, cell dimensions were increased by one percent per cell to a specified maximum. Cell dimensions were held constant at that dimension over the remainder of the domain. With the described discretization, the domain contained 2.579×10^6 cells.

Because the selected free field domain was cylindrical, the simulated charge was built as two stacked disks. The explosive material was modeled with the Jones-Wilkins-Lee (JWL) equation of state (EOS) provided in the Gemini EOS library, and was detonated via Gemini's burn option. The burn option requires a definition of burned and unburned explosive material and converts the explosive material to detonation product as the detonation front travels at a prescribed velocity through the cells (NSWC, 2005). To model the surface detonation conditions, three concentric rings were defined as simultaneous initiation points on the disks' surfaces. The disk charge is shown conceptually in Figure 4, and is shown in the discretized two-dimensional domain in Figure 5.

The remainder of the flow field was loaded with air described by the Gamma-Law EOS. With regard to boundaries of the two-dimensional free field, the top and sides were modeled with a free boundary condition. The bottom, representing the ground surface, was modeled with an idealized reflective boundary condition.

Once the free field calculations were completed, results were mapped into a three-dimensional Cartesian space for the second stage of calculations. Mapping in Gemini is performed through a rezoning routine (NSWC, 2005). To rezone a calculation, a new domain is defined with spatial reference to the original. The new domain is autonomously created with its own discretization and cell material loading, and in areas where the two domains are coincident, properties of the new domain are overwritten by the old. Techniques to load the old domain cell properties into the new are dependent upon whether the old cell is composed of a single material or is mixed. Further information on the mapping technique is provided in the Gemini user's manual.

Figure 3. Explosive charge

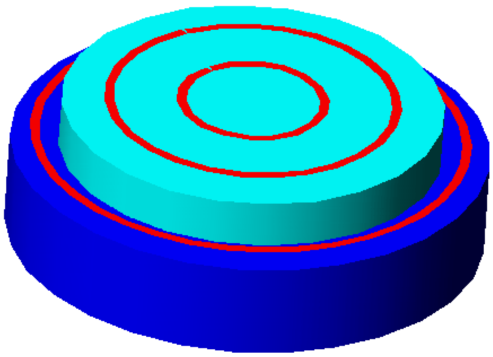

Figure 4. Stacked disk charge with three concentric initiation rings

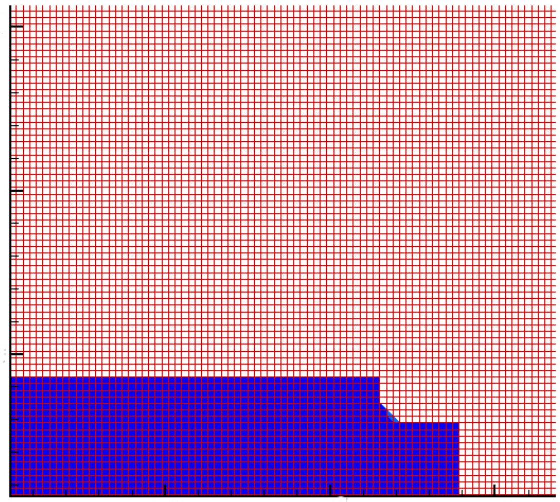

Figure 5. Discretized disk charge

Dimensions of the three-dimensional domain were set at 2,310 cm (direction of shock flow) by 480 cm (transverse to shock flow) by 360 cm (height), resulting in a total cell count of 1.848×10^6. With exception of the ground surface, all boundaries of the three-dimensional domain were modeled as free surfaces. As with the two-dimensional domain, the ground surface was modeled as an idealized, perfect reflecting surface.

In the three-dimensional space, the small observation post was modeled with Gemini's "blocked cells" option. In Gemini, blocked cells are treated as rigid material, and their surface is treated as a perfectly reflecting surface (NSWC, 2005). Representation of the observation post in this manner is in agreement with the assumptions made in section two regarding the effects of high structure mass.

The rezoned three-dimensional domain with the discretized structure and a shock front iso-surface is shown in Figure 6.

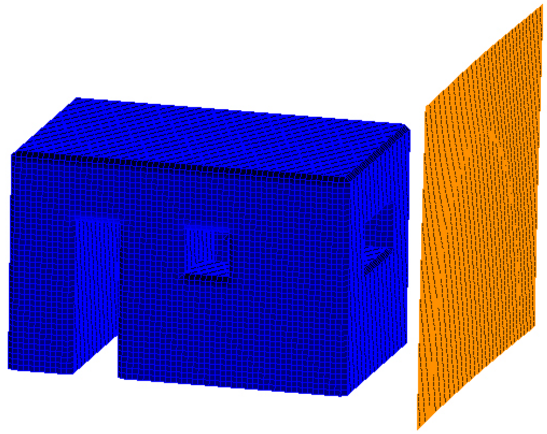

Figure 6. Three-dimensional domain

4. EXPERIMENTAL COMPARISON

Prior to comparing Gemini results to the ADF Trial 845 data, the same free field model was used to simulate a hemispherical charge detonation. This was done to compare results against commonly accepted empirical data, and build a basic confidence level in the model formulation. Results of this calculation are shown in Figure 7. In this figure, peak pressure versus range data was compared to predictions from the USACE code ConWep (Hyde, 2004). ConWep is an implementation of weapons effects calculations contained in Army Technical Manual 5-855-1 (Department of the Army, 1986), which computes air blast parameters via the equations presented in Army Ballistics Research Laboratory Technical Report 02555 (Kingery and Bullmash, 1984). As seen, the results are in very close agreement.

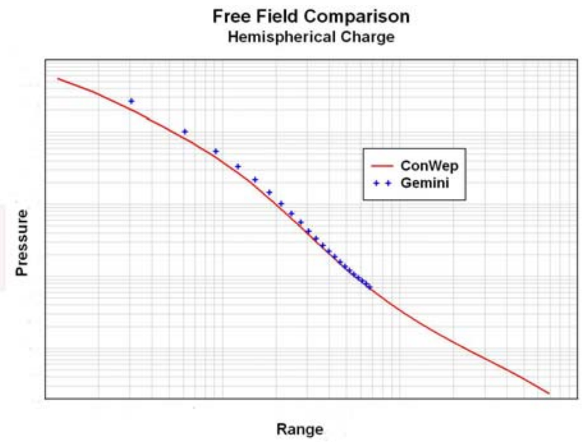

Figure 7. Gemini vs. ConWep

In ADF Trial 845, the small observation post was instrumented with three Kulite Semiconductor XT-190 piezoelectric pressure gages inside the structure (designations SOB2, SOB3 and SOB4). Recorded pressure-time histories for gages SOB2 and SOB3 are shown in Figure 8. Also included is the pressure-time history for an additional incident free field gage, MLVN1. As seen, there was considerable agreement between the Gemini and experimental results. First, the wave forms closely matched the experimental. At gage locations SOB2 and SOB3, the simulation not only accurately computed the initial pressure pulse, but also captured the later peaks that were generated by wave interactions and wall reflections. From the compared data, peak pressure differences were limited to fifteen percent or less. Shock front arrival times also agreed, with computed arrival times within seven percent of the experimental.

Pressure state plots from the simulation are shown in Figure 9, and depict: the shock front prior to impingement, shock reflection on the structure face, shock flow into the structure, and total engulfment of the structure. The contours are shown on a vertical slice through the structure, showing Gemini's capability to simulate complex flow and wave interactions.

From Figure 8, it is noted that a double pressure spike was recorded at MLVN1, but not in the Gemini calculation. However, in reviewing additional model output at lesser standoffs, the double spike was observed. This indicates that the model captured the phenomenon generating the staggered shock front rise, but due to differences in shock front velocity, the second wave overcame the first before reaching the gage location in the model.

To evidence Gemini's capture of the double wave phenomenon, pressure state plots from the two-dimensional free field are provided in Figure 10. As seen, due to the unusual charge configuration and means of initiation, at 5.5 msec after detonation several distinct wave fronts had formed. Near the ground surface, a small uniform front had formed beneath a faster moving, parabolic shaped front. Above these, a larger, more uniform front had expanded and was more characteristic of a shock front that might be expected from a typical hemispherical charge. At 23.5 msec, the two lower fronts had converged into a single uniform wave, but the upper front still remained distinct, and had begun to generate a downward moving wave into the lower, uniform zone. At 52 msec, with the ground wave front at a standoff approaching that of MLVN1, the downward moving front had reflected off the ground surface, and generated a double pressure pulse, as seen in the experimental data. Lastly, at 63 msec and a standoff just surpassing that of MLVN1, the reflected wave merged with the propagating front to form a new, uniform wave.

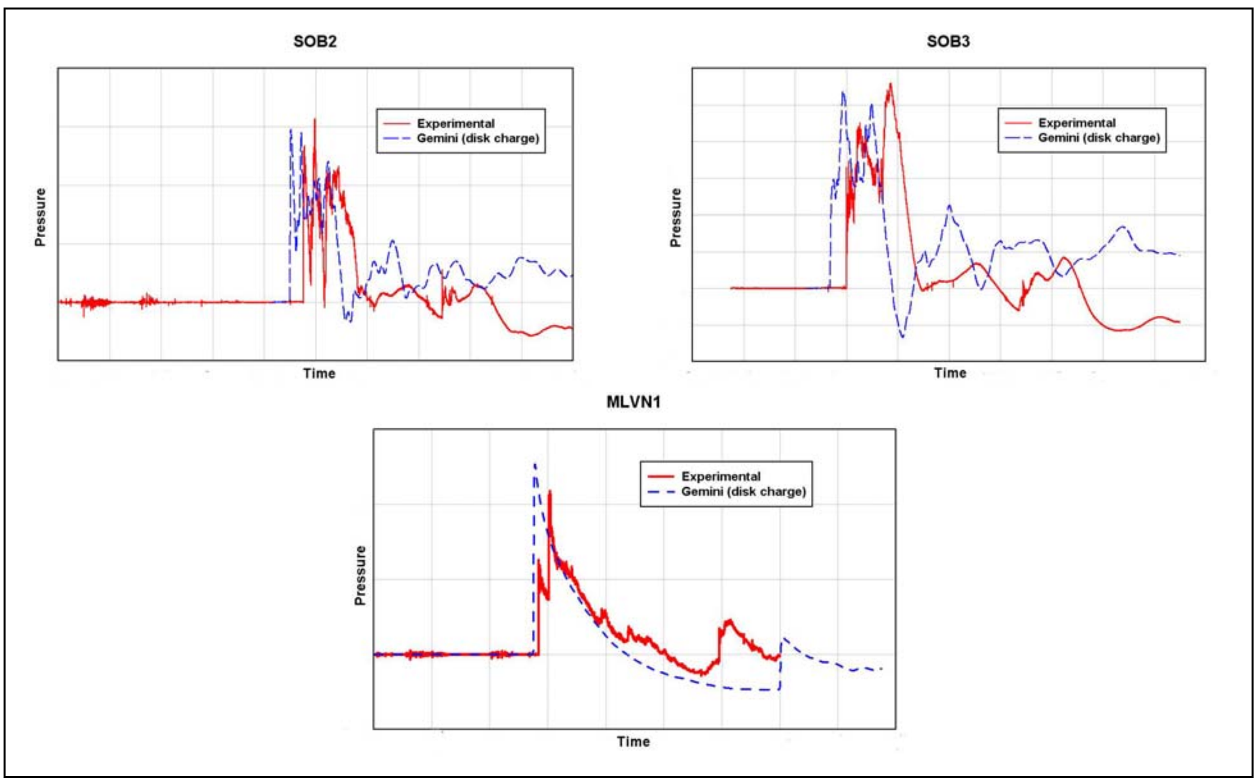

Figure 8. Comparison of experimental data to Gemini simulation

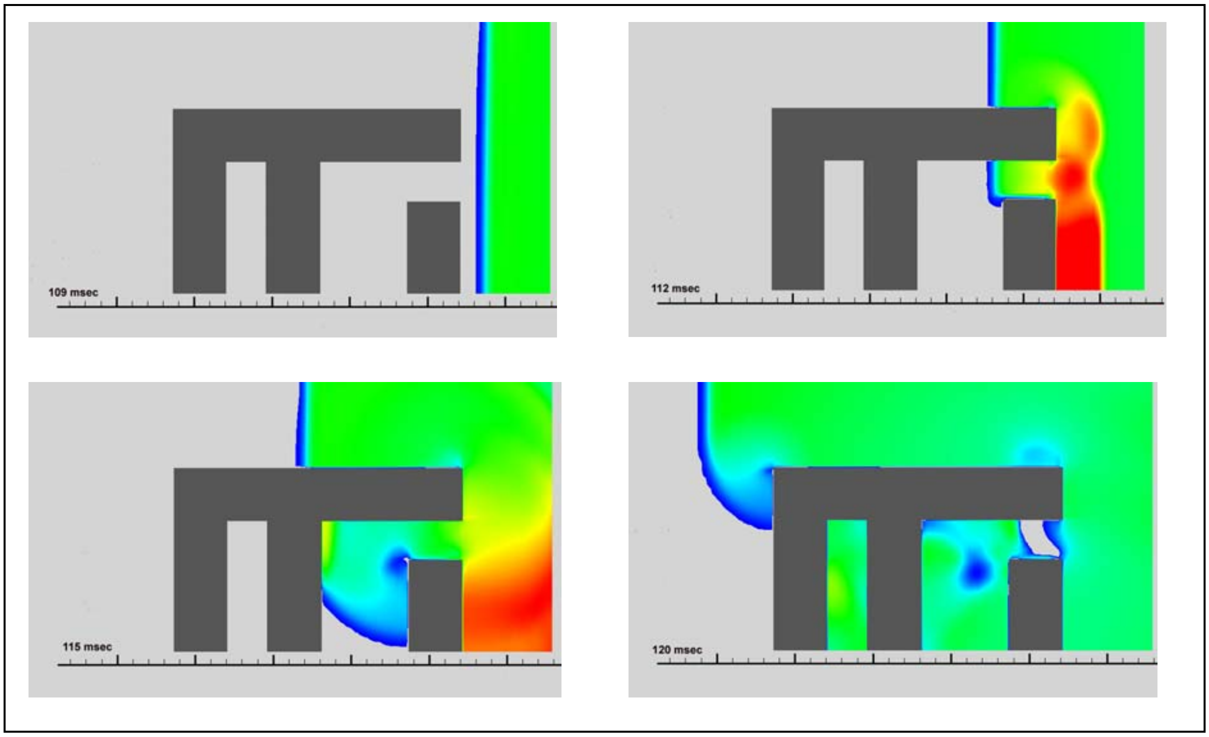

Figure 9. Pressure state plots during structure engulfment

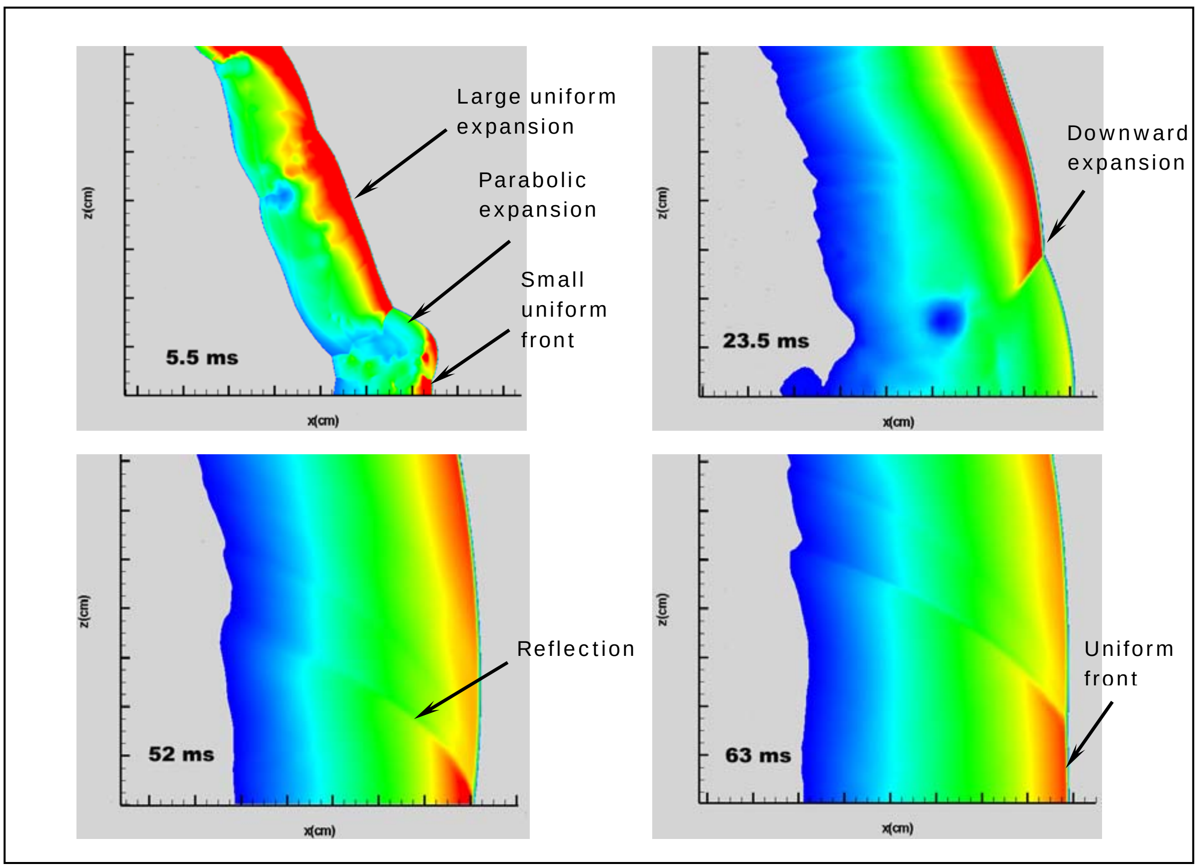

Figure 10. Free field pressure state plots

5. RESPONSE SURFACE

To bridge the gap between first-principles code accuracy and the calculational speed necessary for warfighter assessment tools, a multi-dimensional response surface can be used to predict pressure conditions inside a field fortification. Generally speaking, response surface methodology is a way of relating multiple independent variables contained in a certain process, all of which have some influence on a specific response. Oftentimes, this method is used to optimize the performance of a given process after determining which parameters have the greatest impact on the response of interest. In this case, the parameters of interest were predefined as charge scaled range and azimuth orientation to the structure, and the response of interest was the resulting internal pressure conditions.

To build a response surface, discrete data points defining the relationship between variables are defined, and then statistical methods are used to build a continuum (i.e. response surface) over which the response of interest is computed. Because this is an empirical process, a data set describing the relationship between independent variables and response is required. In this application, generating data through physical experimentation would be costly and impractical. However, accurate calculational tools, such as a first-principles CFD code, could be used to efficiently generate the necessary information. It has been shown that Gemini is capable of accurately modeling blast events and the resulting shock flow in and around a field fortification. Therefore, it is believed that Gemini can be used as a test bed that is virtual rather than physical, and produce the data necessary to generate the response surface.

As an example of how a response surface might be generated for use in a blast effects prediction, the following describes the process for a single azimuth orientation. Because a single orientation is considered, the results effectively generate a two-dimensional curve. However, with the process defined, it is then simple to extend the two-dimensional curve into a three-dimensional domain and generate a full predictive surface.

So that response surface predictions could be compared to experimental data, Gemini simulations were based on the configuration of ADF Trial 859. The orientation between charge and structure was held constant (front window facing the charge), and calculations were performed at determined standoff intervals over a given range. These calculations resulted in computed internal pressure and impulse conditions that could in turn be used to generate a predictive curve. When performing these calculations, a key question was “At what standoff interval must the calculations be performed?” At the onset of modeling, an interval was selected that required 16 simulations per orientation. However, as seen below, it was found that significantly fewer might adequately define the predictive curve.

With the complete set of 16 data points, the design of experiment software Design-Expert® (Stat-Ease, 2002) was used to generate a predictive curve. The curve fit methodology employed in this instance used an inverse transformation of the data and polynomial fitting equations. To determine how many simulations were actually required to adequately predict response, the curve was generated with two data points, three data points, etc., and the point at which the curves began to converge was observed. As seen in Figure 11, even with only three data points considered (end points and mid point) the prediction is close to the 16 point solution. By computing the difference between curves, it was found that using three to five data points resulted in a maximum difference from the full solution of only 10 percent, and when eight points were used (every other point) the difference was reduced to three percent or less. From this, it was indicated that far less than the initially estimated 16 simulations per orientation were required to predict response over the given range. This represents a significant reduction in the overall number of calculations that are in turn required, needing only 20 to 32 simulations (five to eight simulations at four primary orientations) instead of the originally estimated sixty-four. Note that in Figure 11 the accuracy with which the predictive curve matches the Gemini data points is also evident.

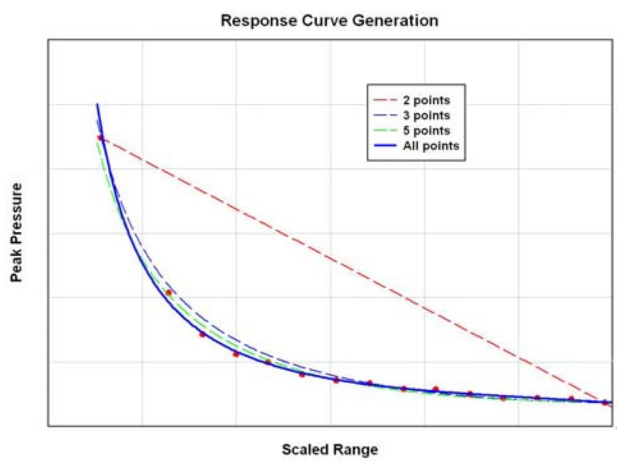

Figure 11. Response curves

With the process defined for generating a predictive curve, expansion to include the full range of structural orientations would yield a three-dimensional response surface similar to that in Figure 12. Shown is a conceptualized response surface generated around the two-dimensional curve described above. Also shown are two validation points from data gathered in ADF Trial 859. These correspond to the orientation for which Gemini calculations were made, and subsequently provide an indication of the response surface methodology’s capability. It is noted that this experimental data validates the surface over only a limited range, and it is therefore important to continue validation comparisons as the surface is extended.

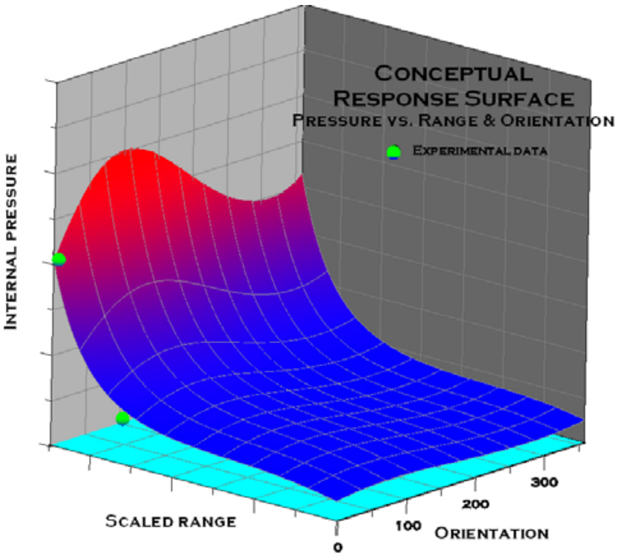

Figure 12. Conceptual response surface

CONCLUSIONS

The purpose of this effort was to illustrate use of the first-principles code Gemini as a virtual test bed for the development of shock data inside a high-mass, expedient field fortification. In turn, the experimental design code Design-Expert® was used to process the data and generate a predictive function capable of estimating shock conditions over a range of independent variables. If shown to be accurate, the resulting predictive function can be fed into warfighter assessment tools such as ATPlanner and can extend their capability to perform vulnerability assessments from a common mode of enemy attack. It is noted that by limiting these predictions to a high-mass structure, several assumptions were made that simplified calculational requirements. However, because this approach is only limited by the accuracy of calculational results, it is expected that other structure types and hazard modes could be considered. This might include next generation expedient protective structures that are lightweight, and to which high-mass assumptions do not apply.

Although Gemini was primarily developed as a naval code for underwater explosion simulations, the comparisons to in-air data have shown promising results. From this, it is concluded that for the explosive and general scenario considered, Gemini is a valid simulation tool, and could be accurately used for response surface population. Moreover, these results generally indicate that due to the ease of use and accuracy of calculations, Gemini could also find application in many other simulations of Army interest. Therefore, additional opportunities should be explored to obtain benchmark data and further validate the code's performance.

At this point, response surface generation has been limited to a single charge orientation with respect to the structure. However, as seen in Figures 11 and 12, the predictive functions have closely matched experimental results. Therefore, the process should be expanded over the range of orientations, resulting in generation of a full predictive surface. To extend the use of this predictive algorithm, instead of developing structure specific surfaces, consideration should be given to expansion of the surface into additional domains. These domains might include variables such as structure and opening sizes, and if shown accurate would further increase the efficiency of this tool.

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